

# Fast Timing Detectors for Forward Protons at the LHC

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I discuss the development of high precision timing detectors for high momentum protons at the LHC, and their application in studying exclusive Higgs boson production.

Measurements of the time of flight (ToF) of particles in high energy physics are usually used to measure the speed of particles between two known space-points and, together with the energy or momentum, to determine their mass and hence identity (usually  $\pi^\pm$ ,  $K^\pm$  or  $p/\bar{p}$ ). Less common is its use to determine the position of origin of an ultra-relativistic particle, or a photon. When two oppositely directed particles are timed relative to each other, with a time difference  $\Delta t$ , one can determine the point of origin  $x$  with a precision  $\Delta x = \frac{1}{\sqrt{2}}c.\Delta t$ , ( $c = 3\text{mm}/10\text{ps}$ ), if they came from the same point, or determine whether they did indeed have a common origin. ToF between two  $\gamma$ -rays can be used for localization of radioactive decays in positron emission tomography, a potentially important application still in the development stage. Precision  $\Delta t$  measurements between two outgoing protons can greatly reduce backgrounds to the exclusive reaction  $p + p \rightarrow p + X + p$  at the LHC, where  $X$  may be a Higgs boson, coming from cases where the outgoing protons do not come from the same  $pp$  collision (pile-up), as first proposed in Ref.[1]. The protons travel in opposite directions along the beam pipes together with the proton bunches until they are deflected sideways (because of their lower momentum) by LHC magnets, where they can be detected in small ( $\approx 1\text{cm}^2$ ) detectors. Precision track measurements ( $\sim 5\mu\text{m}$  over 8m) determine their momentum loss, and hence the mass of the produced state  $X$ . Groups in both CMS and ATLAS are pursuing R&D leading hopefully to approval of these very forward (at 240m and eventually 420m downstream) proton detectors. The physics goal is to measure the properties of states such as the Higgs boson (if it exists) in a unique way. One selects very rare events (of order 1 in  $10^{12}$  collisions) with a Higgs candidate in the central detectors, both protons measured and no other particles produced. Measurements at the

Tevatron or related processes (with  $X = \chi_c, \gamma\gamma$ , di-Jet) provide constraints on the (few fb) cross section [2]. High luminosity must be used with perhaps about 20-30 intersections per bunch crossing, every 25ns. Most  $p + X + p$  events will be pile-up background, with the protons from different collisions, and must be rejected. There are some kinematic constraints, but powerful rejection comes from ToF  $\Delta t$  measurements, and our goal of  $\sigma(\Delta t) = 10\text{ps}$  localizes the collision point, iff they came from the same collision, to  $\sigma(z) = 2.1\text{mm}$ , while the collision region has length  $L \sim 50\text{mm}$  ( $\sigma$ ), and this can be matched to the much better known H (WW etc) vertex. Fortunately the area needed for proton detection is only about  $1\text{cm}^2$ , and the protons have energy near the beam energy of 7 TeV so  $v \sim c$ , and we can put thick (if needed) timing detectors after tracking. Requirements on the detectors are that they be radiation hard to  $\sim 10^{15} \text{ p/cm}^2$  and they must be edgeless, i.e. active within  $\sim 100\mu\text{m}$  of their edge, because we need to detect protons only a few mm from the beam. The edgelessness is a strong constraint on the design. They must also have electronics capable of being read out every LHC bunch crossing (for about 1ns every 25ns). Cherenkov light is prompt and good for timing, and we use that, either in a tube of gas [3] or in quartz (fused silica) bars. We are studying two photon detectors with quartz bars, micro-channel plate photomultipliers (MCP-PMTs) or silicon solid state photomultipliers (SiPMs). I will describe beam tests of each type at Fermilab. The principle of the QUARTIC detector (QUARtz TIming Cherenkov) is that if several long quartz bars are inclined (with respect to the protons) at the Cherenkov angle,  $\theta_{ch} = \cos^{-1}(1/n) \approx 48^\circ$ , and the MCP-PMT face is normal to the bars, the light generated in each bar in the direction of the PMT arrives simultaneously. Consider it as a light wavefront propagating along the bars and parallel to the PMT window. The MCP-PMT can be single-anode, as in the 40mm diameter PHOTEK PMT240, or each bar can be coupled to a different anode pad, as in the Burle/Photonis 85011 (8 x 8 pads each 5mm x 5mm, with  $10\mu\text{m}$  pores). We tested both types. The PMT240 anode design is isochronous; we tested with a PiLas pulsed laser the response at different positions over the window and found it to be the same within measurement errors ( $\leq 2\text{ps}$ ). An advantage of the 8-bar/pad detector is that one makes 8 measurements, each with worse resolution, but that allows the electronics to be less performant per channel, and one should recover a factor  $1/\sqrt{8}$  by combining the measurements. They are not, however, independent as there is both optical and electrical cross-talk between adjacent channels, but with the isochronous design this is not an issue. Another advantage of the 8 x 8 pad detector is that if two protons pass through within the same bunch crossing they may be separately timed, but only if in separate rows and cross-talk is negligible. We have tested both the PMT240 with 1 - 5 bars each 5mm square, and the Photonis with up

to 8 bars in a row.

I discuss first the single anode PMT240 results. The bar housings were made at Fermilab by electro-erosion from a solid block of aluminium. Channels were made for the bars, square with rounded corners such that the bars did not touch the sides, except at the corners, to maintain excellent total internal reflection, TIR, along the bar. A spring applied pressure at the bar-PMT interface, with optical grease (which is probably not needed). We placed two identical detectors A and B (a) On the same side of the beam, with the bars horizontal. In this case the time difference  $\Delta t = t(A) - t(B)$  is independent of the horizontal position of the track; the spread is only 2mm as defined by the trigger counter, but that corresponds to about 15ps time difference! In the experiment and in future tests the track position will be known to  $\sigma(x) \sim 10\mu\text{m}$ . (b) On opposite sides, in which case the time sum should be independent of  $x$  and the time difference proportional to  $x$ , with  $\frac{d\Delta t}{dx} = n/c$ . Even with the constant fraction discriminators (CFD) we found a residual correlation between the time difference  $\Delta t$  and the pulse heights, and we applied a linear “time-slewing” correction. Then the  $\Delta t$  distribution was a good fit to a Gaussian distribution with  $\sigma(\Delta t) = 23.2\text{ps}$ . (The TDC was calibrated with a delay cable.) Comparison with a third reference counter showed that counters A and B had the same resolution,  $16.0 \pm 0.3\text{ps}$  each. The combination A+B treated as a single detector (“double Quartic”), as it will be in the experiment, then has  $\sigma(A+B) = 23.2\text{ps}/2 = 11.6\text{ps}$ . We measured the dependence of the resolution on the number of bars, from 2 - 5, and found  $\sigma(t) = \frac{1}{\sqrt{N(\text{bars})}}$  as expected, showing that the five bars contribute equally; with 5 bars the number of photoelectrons per proton is  $\sim 20 - 25$ .

Using the double Quartic as a reference we made studies with a single 15cm long bar, inclined at  $48^\circ$ , with a PHOTEK 210 (single anode, 10mm diameter) tube. Longer bars have the advantage of having the MCP further from the beam and hence in lower radiation. The main disadvantage is chromatic dispersion along the bar; the more intense blue light ( $\lambda = 200\text{nm}$ ) is slower than red light ( $\lambda = 550\text{nm}$ ) by 3.0ps/cm. We measured a degradation of the time resolution  $\sigma(\Delta t)$  of about 1 ps per cm of extra bar length. The effect of chromatic dispersion can be reduced with color filters on the MCP window. With the proton at the far end of the 15cm bar we tried both red-pass (Edmund Optics 62-974,  $\Lambda(\text{min}) = 400\text{nm}$ ) and blue-pass (EO 49-823,  $\Lambda(\text{max}) = 400\text{nm}$ ) filters, and found the blue-pass filter ( $\sim 15\%$ ) better despite the lower pulse height. The red-pass filter gave about the same resolution as with no filter. This test should be repeated. It has been suggested to replace the quartz bars with quartz fiber bundles; this could give some flexibility in mapping the detector cells to MCP anode pads (in a multi-anode MCP), enabling finer binning near the beam where

the particle density is highest. As an initial test we tried a single fibre bundle with the same dimensions as the bar, and found a  $\sim 30\%$  better resolution and a weaker dependence on bar length. This is a very preliminary and unexpected result; we did not have time to repeat it, but will investigate further, as well as combinations of fiber bundles with filters. A double-Quartic resolution better than our goal of  $\sigma = 10\text{ps}$  is in reach (with adequate electronics).

We also tested a detector with silica aerogel as Cherenkov radiator, with a  $45^\circ$  plane mirror reflecting the light to a PHOTEK240 MCP-PMT. Aerogel is cheap, radiation hard and has a refractive index (which can be tuned in production)  $\sim 1.01\text{-}1.05$  with essentially no dispersion in the visible range. It is however fragile. We used a 25mm long block with  $n = 1.03$ ,  $\theta_{ch} = 13.9^\circ$ , and about 13 p.e. per proton. We measured a time resolution  $\sigma(t) = 31\text{ps}$ . The amount of material in the beam is very small and one could have several such detectors in line to get good resolution. However the light cannot be focussed to a small area, and the large tubes are expensive and close to the beam. One might develop the aerogel idea, e.g. replacing the MCP-PMT with an array of SiPMs.

We tested arrays of SiPMs with quartz bars in front (Q-SiPMs), in line with the beam. For a particle parallel to the axis of a parallel sided bar, all the Cherenkov light is totally internally reflected to the back, for any refractive index, as the Cherenkov angle and TIR angle are complementary ( $\cos \theta_{Ch} = \frac{1}{n} = \sin \theta_{TIR}$ ). We used SiPMs made by STM Catania,IT (with thanks), area  $3.5 \times 3.5\text{mm}^2$ , with 4900 cells of  $50 \times 50\mu\text{m}^2$ ; each cell is an avalanche photodiode. We varied the length of quartz radiator from 5mm to 30mm and found a continuous improvement to  $\sigma \sim 15\text{ps}$  at 30mm (even though the time difference between light arriving from the front and back is then about 120ps). More light helps, even if it is not prompt. In our application we can have many (e.g. 10 - 20) such detectors in line, and fit the many time measurements to a line (“time-track”) similar to multi-layer track chambers. This provides continuous measurements of the resolution, efficiency, and calibration of each detector. Each layer can consist of an array of many individual detectors to provide multihit capability. We tested six Q-SiPMs in-line with 10mm Q-bars, through an ORTEC VT120  $\times 20$  fast pre-amp into a DRS4 “scope-guts” waveform recorder (200ps/sampling). Simply making a linear fit from 10%-90% of the amplitude and extrapolating to zero amplitude was close to optimal, and we found  $\sigma(t) \sim 30\text{ps}$  per detector. An issue is the lifetime of the SiPMs close to the LHC beam, however they could be made for simple replacement every year or so if needed, as they are relatively inexpensive. Alternatively the SiPMs can be at the end of  $48^\circ$  bars as in the QUARTIC, replacing the MCP-PMT. We will test this configuration in 2011. An attractive possibility is to make SiPMs

with a “mini-strip” geometry, e.g. 1mm individually read-out strips, and use a quartz fiber bundle bar at 48° to the beam. This could give independent timing on particles only 2mm apart in  $x$ , and keeps the SiPMs far enough from the beams to minimize radiation damage. With multiple layers, we would emulate track chambers but in the time domain.

The Q-SiPM combination makes a very compact fast timing counter which could be used as a (directional) monitor of particle fluxes just outside the LHC beam pipe, bunch-by-bunch, and with time resolution less than the proton bunch length. The LHC Instrumentation group are looking into this possibility.

An interesting possibility is to develop a “GHz streak camera” using a silicon pixel detector. Photoelectrons from a photocathode are accelerated and focused to a small spot, which can be swept with x-y sweeping electrodes over the pixel detector with the LHC 400 MHz (or other) RF into a circle, converting time into spatial position. I have not developed this idea, but Amur Margaryan at this meeting described a similar project.

Finally I mention two more ideas for rejecting pile-up background in the  $p + H + p$  search, which could be done with large area (many  $m^2$ ) pixellated timing detectors. Covering forward discs with such detectors to time each charged particle arriving there, enables the time of the collision at their origin to be reconstructed. Those events are *background*, as the  $p + H + p$  events do not usually have such forward particles. Even more ambitious, is to cover the central region with good timing detectors to make precision time measurements of all collisions, to correlate with the time from the protons. If thin enough, they might be close to the collision region, with fine enough granularity to time all tracks. Simply (!) add fast timing capability to silicon tracking detectors! Both these schemes could provide additional pile-up rejection.

Some of these results have been published [4]. I especially thank S.Malik, E.Ramberg, A.Ronzhin, A.Zatserklyaniy for close collaboration on the tests.

## REFERENCES

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